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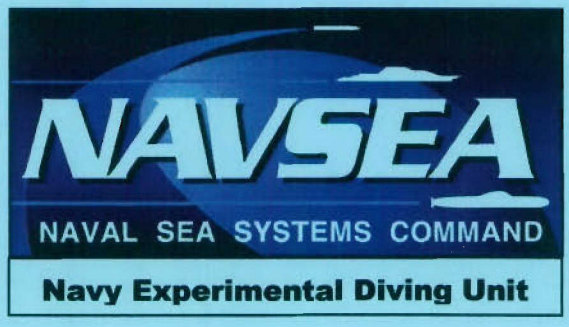
POTENTIAL BENEFITS OF NAVY DIVE COMPUTER USE IN SHIPS HUSBANDRY DIVING: ANALYSIS OF DIVES CONDUCTED ON THE USS RONALD REAGAN (CVN-76)



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19. ABSTRACT

Navy Dive Computers were used to record 23 of 25 air dives performed for ships husbandry on the aircraft carrier USS RONALD REAGAN (CVN76) during summer 2004. For each of the 23 dives, decompression status was assessed from the maximum recorded depth and bottom time according to the U.S. Navy (USN) Standard Air Tables and from the recorded dive profile according to the Navy Dive Computer VVAL-18 Thalmann Algorithm (NDC/VVAL-18). Sixteen of the dives were no-stop dives according to both the Standard Air Tables and NDC/VVAL-18, with the NDC/VVAL-18 allowing an average of 37 additional minutes of bottom time more than the Standard Air tables. Another six dives had depth excursions that put the divers on a USN Standard Air schedule that required decompression stops, which were not taken. On these six dives, the NDC still allowed an average of 25 minutes of additional no-stop bottom time. The one dive remaining required decompression stops according to both the Standard Air Tables and NDC/VVAL-18, but none were taken. The NDC would have prescribed a 15 minute stop during this dive, while the USN Standard Air Tables would have mandated a much longer stop than the NDC would have. The performed dives accrued about half the risk of decompression sickness allowed by the NDC at its limits, according to the USN93 model.

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INTRODUCTION

In an effort to support the multilevel nature of Naval Special Warfare (NSW) diving, the US Navy developed a diver-worn decompression computer named the Navy dive computer (NDC) [1]. The NDC was created to support dives in which the diver switched back and forth between air and a rebreather (MK16 MOD 0) that maintained a nominal diver inspired PO_2 of 0.75 atm. The NDC was approved for use by select Naval Special Warfare commands on January 25, 2001[2]. Newer versions of the NDC have been created[3], including a version specifically requested by NAVSEA to support AIR diving[4].

In order to expand the community of Navy divers approved to use the NDC, particularly to include those that routinely dive within the no-stop limits, and facilitate acceptance of the NDC by these divers, it is necessary to illustrate the benefits that can be derived from use of these devices. Ships husbandry divers, who operate in shallow water with depth excursions dictated by the nature of their tasking, constitute one class of divers for which a large benefit from NDC use is expected.

The decompression guidance provided by the NDCs is updated every second using the actual prevailing depth, and consequently differs from that obtained from conventional tables, which presume a square profile with bottom time spent at the maximum depth attained in the dive. Guidance from tables also incorporates additional safety enhancements from depth and bottom time round-ups. Thus, guidance based on actual real-time information will nearly always allow either more bottom time or less decompression obligation than guidance obtained from conventional tables. However, these bottom time increases or decompression time decreases are obtained at the cost of increased risks of decompression sickness (DCS) eliminating the built in safety factor. Records from actual ships husbandry dives afford an opportunity to examine the trade-offs between increased bottom times that would be allowed by an NDC and the associated increased DCS risks, all in the context of no-stop diving. Any such trade off should be acceptable if an NDC-prescribed no-stop limit, though longer than its corresponding limit in the Standard Air tables, generates the same level of DCS risk as the hypothetical square dive to the tabulated limit.

In summer 2004, a Navy contractor completed 25 surface-supplied air dives to perform ship's husbandry on the aircraft carrier USS RONALD REAGAN (CVN-76). Divers carried Navy Dive Computers[1] (NDCs) to record their depth-time profiles. Recorded profiles were analyzed to determine the additional no-stop dive times that would have been allowed, and the associated increased DCS risks that would have been incurred, if the NDCs had been used to control the decompression requirements for these dives.

METHODS

The present analysis makes use of operational dive profiles collected from 25 ship's husbandry dives conducted on the USS RONALD REAGAN using NDCs.

DATA

Records from NDCs were available for 23 of the 25 dives; smooth logs for these dives were also available from the contractor. For two of the 25 dives, NDCs were not used (Dives 1 and 2) neither NDC records nor smooth logs were available. The divers did not leave the surface for Dives that would have been numbers 10 and 12. A numbering error is apparent in the smooth log, as two dives (both having NDC records) are assigned the number 24, while no dive is assigned number 25. On Dives 7 and 8 the NDCs were left at depth while the divers surfaced and the computers were recovered later; the recorded profiles were truncated at the logged bottom times, and an ascent to the surface at a rate of 30 feet of seawater (fsw) per minute was appended to create corrected dive records.

Table 1 categorizes the dives with respect to decompression stop requirements as prescribed by the U.S. Navy (USN) Standard Air tables[5] for the recorded max depth and bottom time and as calculated by the NDC VVAL-18 Thalmann Algorithm (NDC/VVAL-18) from the recorded dive profile (Figure 1). In the latter calculation, the assessment was based on whether NDC/VVAL-18 prescribed decompression stops to the surface from the point in the recorded profile immediately before the recorded ascent.

Table 1.
Data categorized by decompression stop requirements

Group Number	Group Description	Number of dives
1	No-stop dives under the USN Standard Air Tables	16
2	Omitted decompression dives under the USN Standard Air Tables	6
3	Omitted decompression dives according to NDC/VVAL-18	1
Total		23

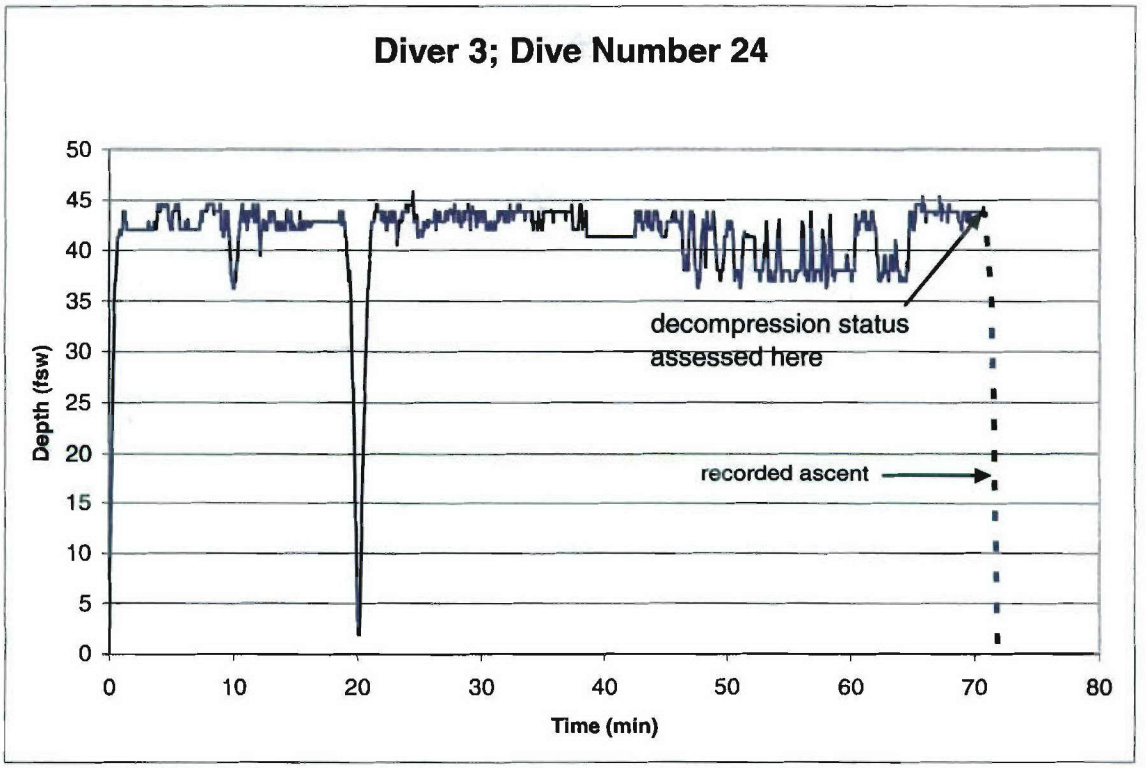

Figure 1. The portion of a recorded depth-time dive profile used to assess decompression status according to NDC/VVAL-18.

ANALYSIS

We compared the remaining no-stop time allowed under USN Standard Air Tables at the maximum recorded depth for each dive to the corresponding remaining no-stop time (RNST) at the maximum recorded depth calculated by NDC/VVAL-18. The behavior of the NDCs for these dives was simulated with the recorded dive profiles run through the NDC/VVAL-18 algorithm implemented on a personal computer. We calculated the RNST time for the NDC/VVAL-18 algorithm by truncating the profile at the start of the recorded ascent to the surface and appending a descent back to the maximum depth followed by the longest time period at this depth from which a no-stop ascent to the surface could be completed at 30 fsw per minute (Figure 2).

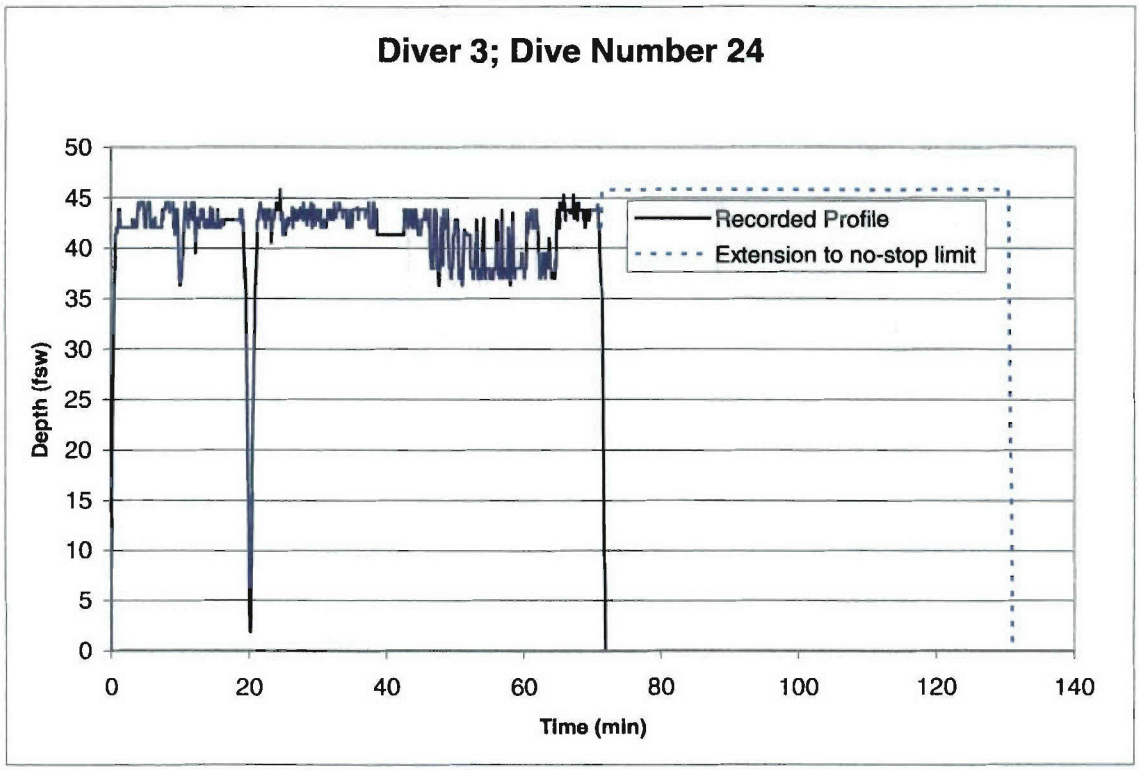

Figure 2. Recorded profile and its hypothetical extension at the maximum recorded depth to the no-stop limit of NDC/VVAL-18.

The USN93[6,7] probabilistic model was used to estimate the risks of decompression sickness (DCS) for the recorded dives and for the hypothetical profiles that included the added no-stop times at the maximum depths.

RESULTS

The recorded maximum depth was greater than the logged maximum depth for all the dives.

Table 2 presents the difference in RNSTs for maximum recorded depths according to NDC/VVAL-18 and for the dives that do not require decompression under the Standard Air Tables. The NDC would have allowed an average of 37 minutes more than the Standard Air Tables for the dives shown in Table 2.

Table 2.
No-Stop dives: Comparison of RNSTs between USN Standard Air tables and NDC/VVAL-18 for the recorded dives

Dive Number	NDC Record		Smooth Log		USN Standard Air		NDC / VVAL 18	
	Max Depth (fsw)	Bottom Time (min)	Max Depth (fsw)	Bottom Time (min)	Table Depth (fsw)	RNST (min)	RNST (min) at Recorded Max Depth	Additional No-stop time (min)
8	45.0	114[1]	42	91	50	9	47	38
9	43.3	90	42	90	50	10	54	44
13	44.8	94	42	93	50	7	44	37
14	44.3	90	42	92	50	11	53	42
16	42.8	92	42	94	50	8	58	50
17	43.5	92	42	92	50	8	56	48
18	43.5	90	42	92	50	8	53	45
19	43.5	94	42	96	50	6	52	46
20	45.3	91	42	95	50	9	32	23
21	43.5	96	42	95	50	4	52	48
22	44.8	87	42	92	50	13	60	47
23	44.0	80	42	83	50	17	57	40
24	43.8	80	42	83	50	20	64	44
24	45.8	71	42	74	50	29	59	30
26	49.8	43	42	53	50	57	65	8
27	49.8	54	42	57	50	46	57	11
							Average:	37.6

[1] *Recorded bottom time was incorrect because the NDC was left at depth when the diver surfaced. Bottom time from the smooth log was used to calculate the indicated RNST.*

The RNST according to NDC/VVAL-18 and the decompression time required by the Standard Air Tables for those dives that required such decompression are given in Table 3. To illustrate the potential influences of errors in the depth readings, this table includes entries for the calculated decompression schedule, or RNST, as if the max depth had been 10 ft shallower than recorded. NDC/VVAL-18 would have allowed an average of 24 minutes of additional no-stop time for these dives.

Table 3.
Omitted decompression dives under USN Standard Air Tables: Calculated RNSTs for NDC/VVAL-18 for the recorded dives

Dive Number	NDC Record		Smooth Log		USN Standard Air			NDC / VVAL-18 RNST (min) at Recorded Max Depth
	Max Depth (fsw)	Bottom Time (min)	Max Depth (fsw)	Bottom Time (min)	Schedule (fsw/min)	RNST (min)	Decompression Time Required (min)	
3	45.5	116	37	116	50/120	N/A	5	35
4	54.3	117	37	117	60/120 50/120	N/A N/A	26 5	27
6	52.8	123	42	123	60/140 50/140	N/A N/A	39[2] 10[2]	19
7	51.0	159[1]	42	116	60/120 50/120	N/A N/A	26 5	19
11	52.3	88	42	87	60/80 50	N/A 12	7	27
15	51.5	91	42	93	60/100 50	N/A 9	14	21
							Average:	24.7

[1] *Recorded bottom time was incorrect because the NDC was left at depth when the diver surfaced. Bottom time from the smooth log was used to calculate the indicated RNST.*
[2] *Ten minutes of decompression was performed for this dive.*

Table 4 gives the decompression times required by both the Standard Air Tables and NDC/VVAL-18 for the one dive that would have required decompression using the NDC. The amount of decompression time required by NDC/VVAL-18 is less than that required by the USN Standard Air Tables.

Table 4.
Omitted decompression dive according to NDC/VVAL-18: Calculated decompression times using the NDC/VVAL-18 for the recorded dive

Dive Number	NDC Record		Smooth Log		USN Diving Manual		NDC / VVAL-18 Decompression Time Required (min)
	Max Depth (fsw)	Bottom Time (min)	Max Depth (fsw)	Bottom Time (min)	Table (fsw/min)	Decompression Time Required (min)	
5	50.3	194	37	194	60/360 50/200	70 35	15

To display the trade-off in increased estimated risk for the longer bottom times allowed by NDC/VVAL-18, the USN93 model's predicted DCS (P_{DCS}) risks for the profiles are provided in Table 5. The predicted risks are shown for the profiles recorded by the NDCs and for profiles that have the additional allowed minutes of bottom time at the recorded maximum depth added to the end of the recorded profile. An average of 44

minutes has been added to the profiles, with a doubling of the average risk to 2.7% when the NDC/VVAL-18 algorithm is used. If the dives are pushed to the limits of the Standard Air Table, the average risk increases to 1.69%, while the risk for the seven dives requiring decompression decreases. For comparative purposes, the estimated DCS risks for 40, 50, and 60 fsw dives to the Standard Air no-stop limits are given in Table 6.

Table 5.
Estimated DCS risks for dives as recorded, and as extended to the NDC/VVAL-18 and Standard Air no-stop limit at the maximum depth for each dive

Dive Number	NDC Record		P_{DCS}, % USN93	Additional minutes at max depth	P_{DCS}, % USN93 Profile with added no-stop time	Additional minutes to Std Air no-stop limit (deco if required)	P_{DCS}, % USN93 Max depth at Std Air no-stop limit
	Max Depth (fsw)	Bottom Time (min)					
3	45.5	116	1.57	35	2.85	+5 @ 10'	1.39[2]
4	54.3	117	2.02	27	3.21	+26 @ 10'	1.62[2]
5	50.3	194	3.10	+15 @ 10'	3.13[1]	+35 @ 10'	2.93[2]
6	52.8	123	1.85	19	3.14	+39 @ 10'	1.69[2]
7	51.0	116	1.78	19	2.66	+26 @ 10'	1.36[2]
8	45.0	91	1.52	47	2.81	9	1.70
9	43.3	90	1.40	54	2.74	10	1.61
11	52.3	87	1.43	27	2.05	+14 @ 10'	1.16[2]
13	44.8	93	1.55	44	2.79	7	1.70
14	44.3	89	1.41	53	2.81	11	1.62
15	51.5	93	1.62	21	2.42	+14 @ 10'	1.24[2]
16	42.8	92	1.38	58	2.85	8	1.53
17	43.5	92	1.41	56	2.81	8	1.56
18	43.5	90	1.46	53	2.82	10	1.65
19	43.5	94	1.47	52	2.81	6	1.57
20	45.3	91	1.79	32	2.61	9	1.94
21	43.5	96	1.41	52	2.82	4	1.52
22	44.8	87	0.98	60	2.83	13	1.48
23	44.0	80	1.35	57	2.82	20	1.75
24	43.8	80	1.26	64	2.80	20	1.62
24	45.8	71	1.29	59	2.75	29	1.86
26	49.8	43	0.62	65	2.48	57	2.23
27	49.8	54	0.90	57	2.47	46	2.12
Average			1.35	44	2.69		1.69

[1] *Omitted decompression dive under NDC/VVAL-18; the P_{DCS} is for the dive with the 15 minutes of required decompression.*
[2] *Omitted decompression dives using Standard Air tables; the P_{DCS} is for the dives with the required decompression.*

Table 6.
Estimated DCS risks of Dives to Selected Standard Air no-stop limits.

Depth	No-stop Limit	P_{DCS}, % USN93
40	200	4.019
50	100	2.547
60	60	2.127

DISCUSSION

In every dive recorded, the maximum recorded depth is greater than the logged maximum depth. The only two values logged for maximum depths are 37 fsw and 42 fsw. The maximum recorded depth for every dive exceeds 42 fsw. In six of 23 dives, the difference between logged and recorded maximum depth is sufficiently large to change the dive from a no-stop dive to one that requires decompression under the Standard Air Tables. In one additional case (Dive 6) decompression was performed, but it was insufficient for the recorded maximum depth. The largest difference between recorded and logged maximum depths occurred on Dive 4, when the maximum depth was logged as 37 fsw and recorded as 54.3 fsw. The largest change in decompression requirements due to a change from logged to recorded maximum depth occurs for Dive 5, for which NDC/VVAL-18 would have required 14 minutes of decompression. USN Standard Air Tables would have required 35 minutes of decompression for Dive 5 if the max depth had been less than 50 fsw, and 70 minutes of decompression for the recorded maximum depth of 50.3 fsw. One explanation for these differences in maximum depths between the logged and recorded depths and the lack of variation in the logged depth is that the logged depths could be based on the internal pressure of the cofferdam.

The depth gauge used to control decompression was not the NDC but a separate device that may have displayed a shallower depth than that of the NDC. Depth reading differences between two accurate gauges can result from placement or from allowed sensor accuracy limits: the NDC's required accuracy is ±2 fsw shallower than 60 fsw. While the divers were working in the cofferdam, their practice was to remove the NDC data recorders and leave these in the water beneath them. As a result, the NDCs recorded depths a few fsw deeper than the divers actually experienced, this increase in depth would reduce the benefits of using the NDC when compared against the Standard Air Tables. Where the NDCs were attached to the divers and how consistent the placement was between dives are unknown. A general observation of the dive records reveals that the monotonous depth readings indicating a computer left in place does not occur at the maximum depths recorded.

The NDC would have provided the divers an average of 37 additional minutes of bottom time for those dives categorized as no-stop dives under the Standard Air Tables. The NDC also would have allowed 24 minutes of additional bottom time for those dives that were categorized as omitted decompression dives under the Standard Air Tables. For the dive for which NDC/VVAL-18 would have required decompression, the USN

Standard Air Tables would have required two to four times more decompression than the NDC/VVAL-18 requires.

Table 5 indicates that the additional bottom time that the NDC allows for the profiles is bought with an increase in the average predicted risk to twice that for the recorded dives. When the profiles are compared to those that could have been performed with the Standard Air Tables (final column of Table 5), a 1 percent additional risk still remains with the use of the NDCs. This risk increase is due to the NDCs use of the actual pressure profile which removes the conservatism due to rounding up the maximum depth to a table depth to determine allowed dive duration. These risk are in line with the risks of diving the Standard Air tables at their tabulated depths for the no-stop limits (See Table 6), and thus are considered acceptable.

CONCLUSIONS

The NDC would have permitted more no-stop time than the USN Standard Air Tables permit, but at an increased risk. This increase in risk is nominal and is acceptable for no-stop diving.

The quality of recorded dive profiles was generally good but was somewhat compromised by differences between logged and recorded maximum depths, locations of the NDC data recorders with respect to diver position during each dive, and uncertainties in pressure gauge calibrations.

Dive records and logs differ in demonstrably important ways.

RECOMMENDATIONS

To improve the quality of the acquired data, we recommend that an NEDU representative or an NEDU-trained data collection coordinator be sent to supervise operational dive data collection efforts.

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